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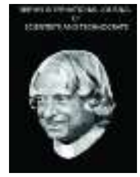

RESEARCH ARTICLE

Analysis of Honey Comb Based Insulation for Cored Brick Heater

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ABSTRACT

The project deals with the insulation of a heater inside which the air is being circulated at 1800℃ and the outer shell is maintained at a temperature of less than 100℃. There are only limited materials available which can bear such high temperatures. Though some materials are available, they possess high densities: say, corundum mulliete which has higher temperature resistance but has high density. To compensate this, we use the material by making it in the shape of honeycomb. Different related studies reveal that honeycomb has more temperature drop than normal solid material. Other materials such as microsil, cera blanket, SA-516, whose thermal properties are flexible for insulation, have been used. The modelling and numerical analysis work has been carried out using various tools such as Creo 4.0, ANSYS 17.0 etc.; and, to validate the results of the numerical analysis, experimental analysis is being carried out. The experimental analysis is done by using infrared heating setup for various models by heating to specific temperatures for a certain period of time to find out the heat flow rate for the known thermal conductivity of the material. The experiment is concluded by finding out the thermal and physical properties of the material along with variations in temperature profiles that are used inside the heater for insulation by the results obtained of numerical and experimental analysis.

Keywords: Honeycomb based insulation, High temperature insulation, Temperature drop, Infrared heating setup, Heat flow rate.

1. INTRODUCTION

Heat is something that appears as a result at the boundary due to a difference in temperature or change of the state between the system and the surroundings. Heat appears only at the boundary while the change takes place inside the system. Sign convention: If heat flows from system to surroundings, then the heat flow is taken to be positive; and, if heat flows from surroundings to system, it is taken to be negative.

1.1. Modes of heat transfer

There are three modes of heat transfer viz

- Conduction
- Convection
- Radiation

1.1.1. Conduction

The conduction is a mode of heat transfer which takes place inside a solid material only due to lattice vibration and transfer of free electrons. Conduction is governed by Fourier law of heat conduction.

1.1.1.1. Fourier's law of heat conduction

This law states that, for a homogeneous solid, the rate of heat flow is directly proportional to the area of section at right angles to the direction of heat flow and to the change of temperature with respect to the length of the path of heat flow.
Mathematically as shown in equation (1.1),

$$Q = -k.A\frac{dT}{dx} \tag{1.1}$$

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where
k= constant of proportionality, also known as thermal conductivity of the body.
A= Surface area of heat flow (m^2)
dT= Temperature difference of the faces of block (K or ^oC)
dx= Thickness of body in direction of flow (m)
Q= Heat flow through the body per unit time (Watts)

1.1.2. Convection

The convection is a mode of heat transfer which takes place between two phases, say solid to liquid or solid to gas due to the temperature difference. Convection is governed by Newton's law of cooling which states that the coefficient of convective heat transfer (h) is defined as "the amount of heat transmitted for a unit temperature difference between the fluid and unit area of surface in unit time."

1.1.3. Radiation

The radiation is a mode of heat transfer that takes place between two materials without any medium (vacuum).

Radiation is governed by three laws:

i. Planck's law
ii. Wien's law
iii. Stefan-Boltzmann law

1.1.3.1. Laws of radiation

Wien's Law: It states that the wavelength λ corresponding to the maximum energy is inversely proportional to absolute temperature T of hot body as in equation (1.2).

$$\lambda_m T = \text{Constant (or)} \lambda m \propto \frac{1}{T} \qquad (1.2)$$

Stefan-Boltzmann Law: The emissive power of black body is directly proportional to fourth power of absolute temperature.

2. INTRODUCTION TO PRE-HEATER

The regenerative air pre-heaters absorbs waste heat from cored bricks, then transfers this heat to incoming cold air by means of continuously rotating heat transfer elements of specially formed metal plates. It is simple in design and has high efficiency due to which most of the heat equipment system uses regenerative air pre-heaters.

2.1. Purpose of storage heater

Here the primary function of the heater is to heat the specified mass of air to a specified temperature. The storage heater which consists of cored bricks heats up the air to a desired temperature of air. The air heater performs 3 cycles. They are,

1. Heating cycle
2. Blow-down cycle
3. Reheat cycle

2.2. Heating cycle

In this cycle, air is heated at a rate of 0.1kg/s by passing through electrical heater for about 6-8hours which in turn heats the cored brick which stores the heat energy and is further used for the blow down cycle. The cored brick is made of ceramics which can withstand high temperatures.

2.3. Blow-down cycle

The blow-down cycle is performed after heating cycle, where the air is introduced from the bottom of the pressure vessel and made to pass through the cored bricks, and the engine valve is turned on and simultaneously air heating valve is turned off. The air gets heated up as it passes through the cored bricks. The temperature of the air depends on the temperature level near the top of the matrix. The blow-down period is measured in seconds.

2.4. Reheat cycle

In this cycle the engine valve is closed and air heating valve is opened, such that the electrical heater starts supplying hot air similar to heating cycle in order to keep the cored brick at the desired temperature. The majority of the exposed surfaces were phenolic insulators with Ethylene Propylene Diene Monomer (EPDM) rubber used in low velocity area. The throat and step were fabricated from an alloy of molybdenum rhenium [1].

The insulating materials and the materials used in the heater are as follows:
Cored brick-corundum mullite
Insulation 1 (ring) - corundum mullite
Insulation 2 (honeycomb) - solid phase is corundum mullite (2 layers with thermal conductivities 4, 2, 1 w/m-k respectively)
Insulation 3 - microsil
Insulation 4 - cera-blanket
Outer shell – SA - 516

Figure 1 represents the heater dimensions and the honeycomb properties are specified in Table 1. The insulation properties are given in Table 2.

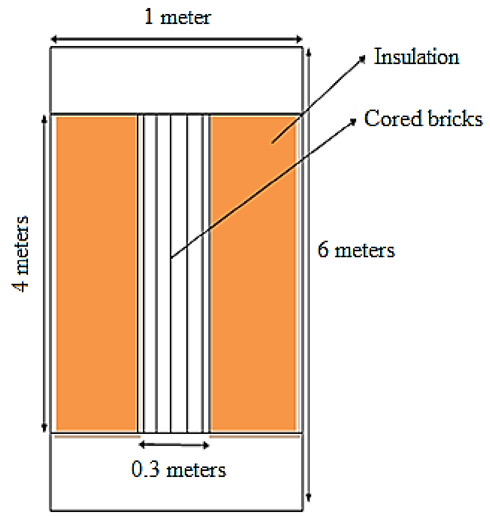

Figure 1.Heater dimensions

Table 1.Honeycomb properties

	Thickness	Thermal conductivity
Layer-1	50 mm	2
Layer-2	50 mm	1

Table 2.Insulation properties

Material	Thermal conductivity (w/m-k)	Specific heat (J/Kg-K)	Density (Kg/m^3)	Thickness (mm)
Corundum mullite (ring)	4	1100	3000	50
Corundum mullite	2	1100	3000	50
Corundum mullite	1	1100	3000	50
Microsil	0.038	1047	250	160
Cera blanket	0.21	1047	128	25
SA-516 (shell)	29.1	710	7750	25

Mullite is a material having excellent mechanical properties at elevated temperatures. When it is mixed with the material, say corundum, it improves the mechanical and thermal properties of the resultant matrix [2, 3]. Heat treatment results in a stabilized phase. Plasma sprayed mullite showed the smallest amount of shrinkage (.43% at 950-980^{0}C). The sprayed materials have lowered modulus and strength but increased the strain tolerance [4]. Yittriastabilized zirconia, is not only used because of its low intrinsic thermal conductivity but also of its high fracture toughness [5].

3. HONEYCOMB STRUCTURE AND ITS MODES OF HEAT TRANSFER

It is a composite structure which can be used to reduce weight for the same structural strength; and, it also acts as a better insulator with minimum material.Honeycomb with square cell shape serves as a best insulation reducing the space required for the insulation and also its weight [6]. The fluid which is enclosed in the honeycomb structure prevents the convective heat transfer between the hot flow air and the honeycomb structure and thus acts as an additional insulation material [7].

The apparent thermal diffusivity and conductivity generally increase with temperature; and, the square channel exhibited low thermal conductivity value than the triangular channel [8]. It can be modelled like a composite brick having two different thermal conductivities. As air is a better insulator, it is an advantage for insulation. The major mode of heat transfer is by conduction. Radiation effect can be considered only when the temperature is above 600K. The convection will play a part in heat transfer if there are large air gaps and Rayleigh's number is greater than 2000.

In honeycomb we can observe all the three modes of heat transfer, but all of them do not have an equal effect. The major part of heat transfer is due to conduction. As it progresses, at high temperatures, the radiations become the critical mode of heat transfer [9]. Radiation heat transfer becomes more critical at higher temperatures [10]. If the porous material is very long and wide in both the vertical and horizontal directions, the velocity and temperature fields repeat themselves in successive enclosures except at boundaries. This helps in numerical analysis of the honeycomb model [11]. Since radiation heat transfer is the main heat transfer mode, we should reduce the radiation heat transfer to diminish the equivalent thermal conductivity which could be done by introducing glass or rock wool in the cavities of the core [12].

Emissivity of the insulating material drops quickly at the higher temperatures than that of original emissivity. To improve the emissivity, we can apply "Enecoat"; and, it also improves the strength and surface properties of the material [13]. Ultra-high temperature ceramics offer good

resistance to oxidation at higher temperatures (>1500^{0}C) as it forms a glassy protective layer, which slows down the oxygen diffusion through this oxide layer [14-16].

4. CRITICAL RADIUS OF INSULATION

The critical radius of insulation plays a major role while insulating the cylinders. The critical radius of insulation is defined as the radius of insulation at which the thermal resistance is minimum, and the heat flow rate is maximum. Figure 2 shows the critical radius plot.

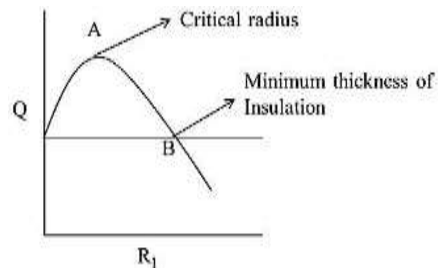

Figure 2.Critical radius plot

For cylinders, R-critical = k/h
For sphere, R-critical = 2k/h

The overall effective thermal conductivity of insulation was found and the value was k = 2.5 w/m-k.

The critical radius of insulation was found out by using the equation (4.1).

$$R - \text{critical} = k/h \qquad (4.1)$$

where
h = heat transfer coefficient =15w/m^2 k
R - critical = 0.166 m

When we observe the insulation of the heater, the first layer of insulation (ring) is starting from 0.15 m and is ending at 0.2 m which means that the critical radius is falling inside the ring material itself and so the critical radius of insulation does not affect the heat flow rate, and the thermal resistance, in this case. According to the graph point ‘A’ is of radius 0.166m.

5. HEAT FLOW RATE CALCULATIONS

The flow rate ‘Q’ is calculated by the equation (5.1)

$$Q = \Delta T/R \qquad (5.1)$$

where
ΔT = temperature difference
R = total thermal resistance

The thermal convective resistance is given by equation (5.2)

$$R = 1/(h * A) \qquad (5.2)$$

where
h = convective heat transfer coefficient
A= convection affected area

The thermal conductive resistance of cylindrical wall is defined by equation (5.3)

$$R = (\ln(rn/rn - 1))/2\prod kl \qquad (5.3)$$

where
k= thermal conductivity of material
l= length of the material

There are total six resistances, such as R_1, R_2…… R_6.
where R_1, R_6 - thermal convective resistances
R_2, R_3…R_5 - thermal conductive resistances

Therefore, the total thermal resistance,
$R = R_1+R_2+R_3+R_4+R_5+R_6 = 0.59$
ΔT = 1700 K

By substituting all the resistances and temperature difference values, the heat flow rate was found to be 2.878 KW.

6. RESULTS AND DISCUSSIONS

Here analysis of heater is carried out in two ways,

1. Numerical
2. Experimental

In order to find out the insulating properties of the designed geometry numerical analysis was carried out initially. In order to validate the numerical analysis, experimental analysis has been done.

6.1. Numerical analysis

Initially, the required geometry has been modelled using CREO parametric 2.0 and analysis has been done using ANSYS work bench 17.0. The meshing has been done using ICEM CFD for three different configurations of honeycomb. The solver used was FLUENT 17.0.

To match the thermal behaviour of composite material by an equivalent homogeneous semi-transparent conductive medium effectively, we are using a new modeling approach called Homogenous Phase Approach (HPA) [17]. Based on the different flow rates, different flow time, different

materials and different thicknesses, we are finding out the optimum thickness of each and every layer of the insulation [18]. Two types of geometries were considered for the analysis.

6.1.1. Geometry 1

The insulation as shown in figure A1 consists of a ring, honeycomb, microsil, cerablanket and shell. The honeycomb geometry on which the analysis has been carried out has an air gap of 4mm and wall thickness of 0.75mm.

The mesh details are as follows:

Number of elements: 232125
Number of nodes : 1022140
Type of element : Quad

Boundary conditions

Inner surface : 2000k
Outer surface : 295.15K
h=155.7 w/m^{2}k

Results:

Ring - honeycomb interface : 1980.7K
Honeycomb-microsil interface: 1869.3K
Microsil-cera blanket interface: 295.61K
Cera blanket –shell interface: 295.39 K

6.1.2. Geometry 2

The insulation consists of a ring, honey comb, microsil, cerablanket and shell. The honeycomb geometry on which the analysis has been carried out has an air gap of 3mm and wall thickness of 0.5mm. Numerical analysis of geometry 1 and 2 are shown in figures A2 and A3 respectively.

Boundary conditions

Inner surface : 2000k and h=155.7 w/m^{2}k
Outer surface : 295.15K
Radiation : Emissivity0.86, 1940K

Temperature

Ring - honeycomb interface: 1989.9K
Honeycomb-microsil interface: 1884K
Microsil-cera blanket interface: 398K
Cera blanket –shell interface : 341K

6.2. Experimental analysis

The experiment analysis is carried out to validate the results of numerical analysis. The experiment is done only on the honeycomb structure for different configurations. The main aim of the experiment is to find out the heat flow rate when it is subjected to higher temperatures at one end and the opposite end is kept open to atmosphere, whereas all the other sides are insulated. The thermal conductivity of the material can be found by this experiment. The thermal resistance of the material can be found using the temperature difference, with which we can find out the effective thermal conductivity of the material [19, 20]. The R-type thermocouple is used for temperature measurement. The honeycomb model has the following configurations:

Model-1:

150*150*40mm, the individual cell dimensions are 0.75*4mm.

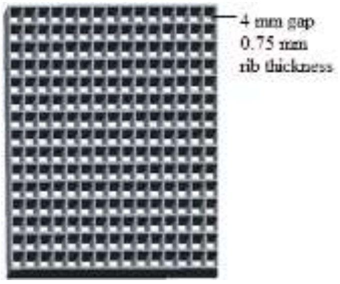

Figure 3.Honeycomb sample 1

Figures 3 and 4 relate the honeycomb samples.

Model-2:

76*76*11mm, the individual cell dimensions are 0.75*4mm

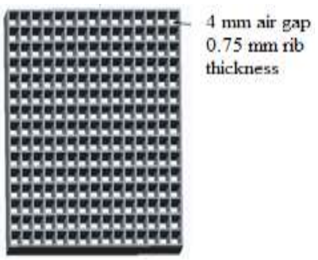

Figure 4.Honeycomb sample 2

7. EXPERIMENTAL SETUP

The experimental setup as shown in figure 5 consists of an infrared heater, where the honeycomb samples are insulated on four sides and kept on the base plate in such a way that one side faces the IR heater and the other is open to atmosphere. The thermocouples are cemented to both the faces i.e., face that is facing the heater and the opposite sides to find out the temperature variations during the experiment. The distance between the honeycomb

and the IR heater is around 40mm. The experiment is carried out in multiple stages of heating and dwelling for a certain period of time till the steady state is reached and results are taken at that instant.

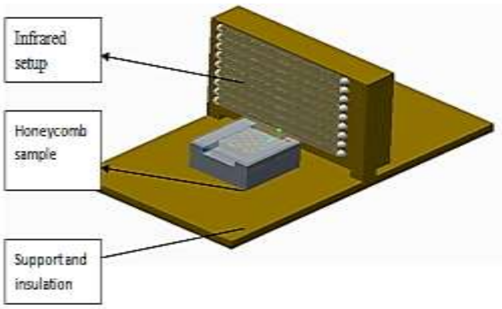

Figure 5.Experimental setup

7.1. Procedure

The experiment was conducted for a certain period of time by heating at certain temperatures and keeping it constant for a certain period, which is termed dwelling and it is done for certain stages to attain equilibrium throughout the honeycomb. The thermocouples are connected on the front, back and side walls of the honeycomb during heating to find out the temperatures. The aim of this experiment was to find out heat flow rate for the known thermal conductivity of the material. The graphs are being plotted during the experiment which shows the variation of temperature with respect to time.

Trial-1:

The specimen was heated using an infrared heater. The time allotted for heating is 60 minutes. It was done in six stages:

1. Heating up to 500°C for 10 minutes
2. Dwelling at 500°C for 10 minutes
3. Heating up to 800°C for 10 minutes
4. Dwelling at 800°C for 10 minutes
5. Heating up to 1000°C for 10 minutes
6. Dwelling at 1000°C for 10 minutes

Dwelling is done to let the specimen stabilize at that particular temperature. Although the duration was about 60 minutes, steady state could not be achieved and so another trial with increased duration is done.

In figure A4, a graph has been plotted by taking the time (seconds) on X-axis and temperature (deg^{0}C) on Y-axis. The top two lines represent the front wall temperatures (thermocouples A, B), middle two lines represent the side walls temperature (thermo couples C, D) and the bottom two lines represent the back wall temperatures (thermo couples E, F). The graph indicates that the front wall has been raised to 500^{0}C for10 minutes and dwelled for 10 minutes and then raised to 800^{0}C for 10 minutes and again dwelled for 10 minutes at that constant temperature and finally raised to 1000^{0}C for 10 minutes and dwelled for another 10 minutes. Dwelling is done to achieve equilibrium at that particular temperature. The complete experiment was carried out for 60 minutes to make sure that steady state is achieved but we could not achieve the steady state; and so, trail 2 has been carried out.

Trial-2:

The intention was to check if the specimen will reach a steady state for an increased duration of about 90 minutes. So it was done in four stages:

1. Heating up to 500°C for 10 minutes
2. Dwelling at 500°C for 10 minutes
3. Heating up to 800°C for 10 minutes
4. Dwelling at 800°C for 60 minutes

It was observed that there was no steady state although the change in temperature came out to be very less for the last 10 minutes with a rise in temperature of about 20°C.

The real time temperature, which the honeycomb experiences, is about 2000°K; but, the maximum temperature was about 1000°C in the experiment. So, in order to simulate the real time conditions, we are extrapolating the results to 2000K.

The graph has been plotted by taking time (seconds) on X-axis and temperature (deg^{0}C) on Y-axis as shown in figure A5. The top two lines represent the front wall temperatures (thermocouples A, B), middle two lines represent the side walls temperature (thermocouples C, D), and the bottom two lines represent the back wall temperatures (thermocouples E, F).

The graph indicates that the front wall has been raised to 500^{0}C for10minutes and dwelled for 10minutes and then raised to 800^{0}C for 10minutes and again dwelled for 60minutes at that constant temperature. Dwelling is done to achieve equilibrium at that particular temperature.

We could not achieve steady state here also but we can consider it as near steady state and can be used for calculations.

8. CONCLUSION

By going through all the different kind of refractory materials which even poses high insulating properties at such high temperature (2000K), it was found that only certain materials can bear such high temperatures without losing their physical and thermal properties and keep the shell at temperature less than or equal to 400K. The materials such as corundum mullite, microsil and cera blanket are found to be the suitable materials for this particular heater insulation. By the addition of honeycomb structured insulation we were able to add an additional insulation, irrespective of the material. To find out the temperature drop and the materials capability to sustain the temperatures, two kinds of tests both numerical and experimental are being performed on the Creo modelled structure of series of insulting materials. So, by comparing both the experimental and numerical analyses, it can be concluded that the materials which were selected are appropriate and meet the necessary requirements.

The materials are as follows:

1. Material 1- corundum mullite (ring)
2. Material 2- honeycomb – 4* 0.75mm
3. Material 3- microsil
4. Material 4- cera blanket
5. Material 5- SA-516

9. FUTURE SCOPE

Here, honeycomb structure is being used which has the following advantages:

1) Adds additional resistance due to air gaps, which has less thermal conductivity than the solid material.
2) The Weight of the structure gets reduced, due to less usage of material.

For honeycomb specially, 4mm air gap and 0.75mm wall thickness is offering more resistance than the other combinations. The materials such as microsil and cera blanket offer high resistance to heat flow at high temperatures (say 2000K). Therefore, these materials can be opted for high temperature insulating applications in near future.

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APPENDIX

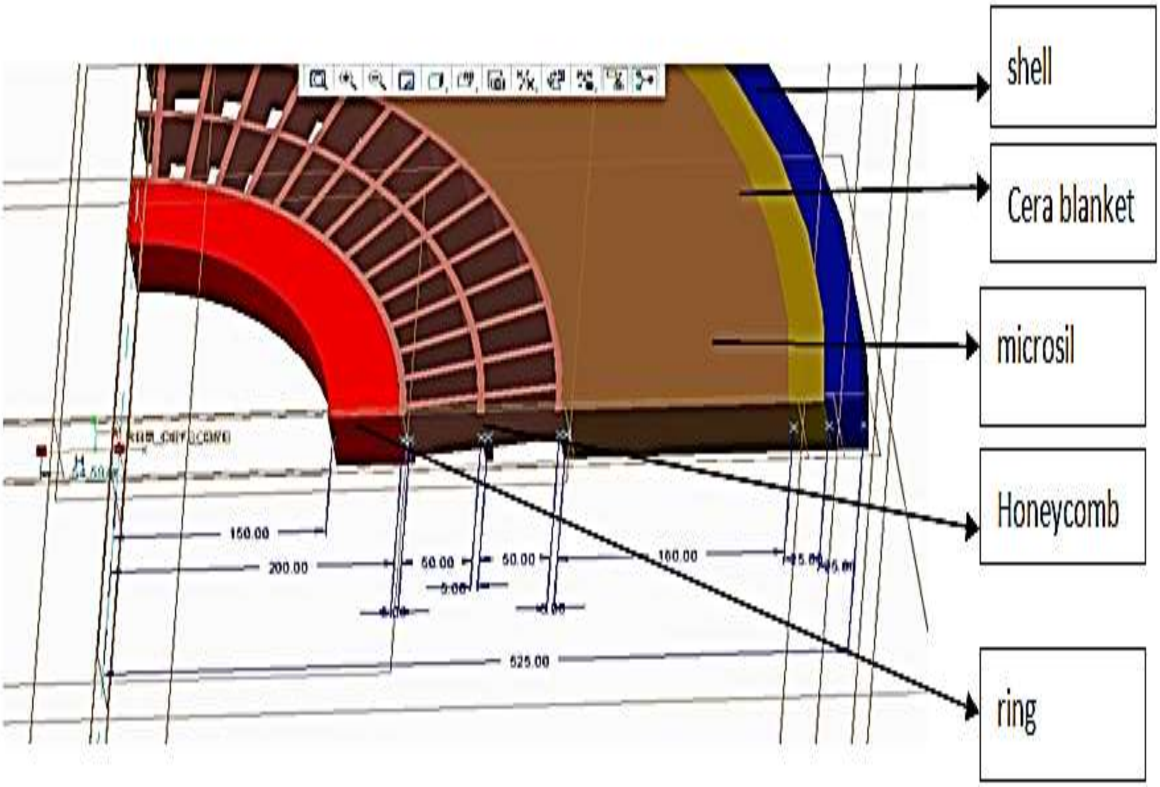

Figure A1.Insulation

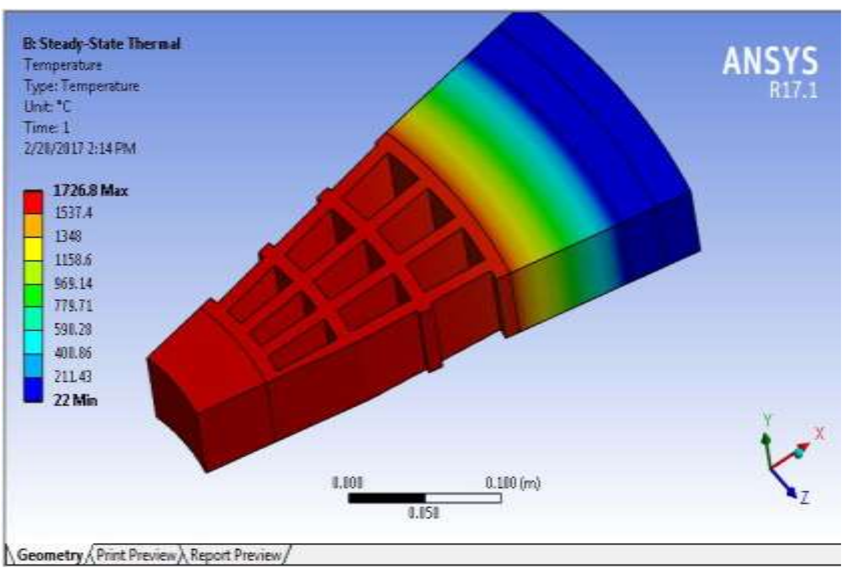

Figure A2.Numerical analysis geometry 1

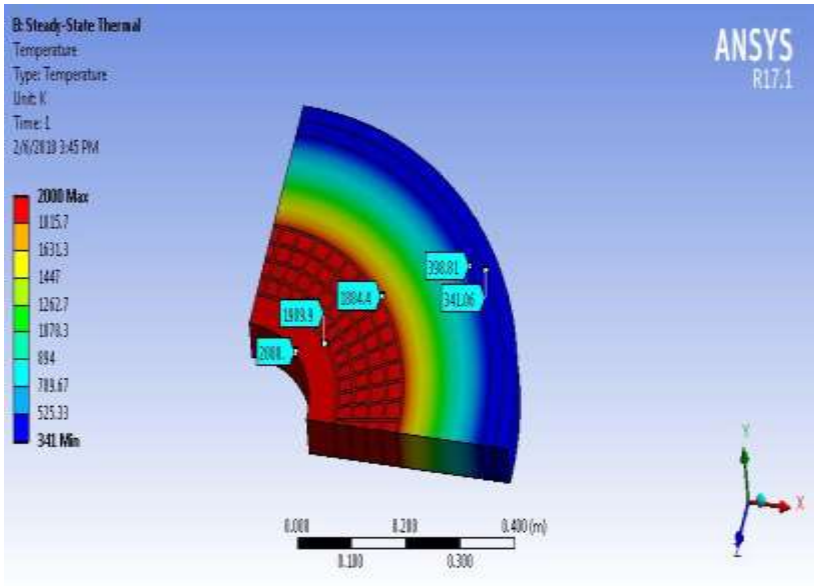

Figure A3.Numerical analysis geometry 2

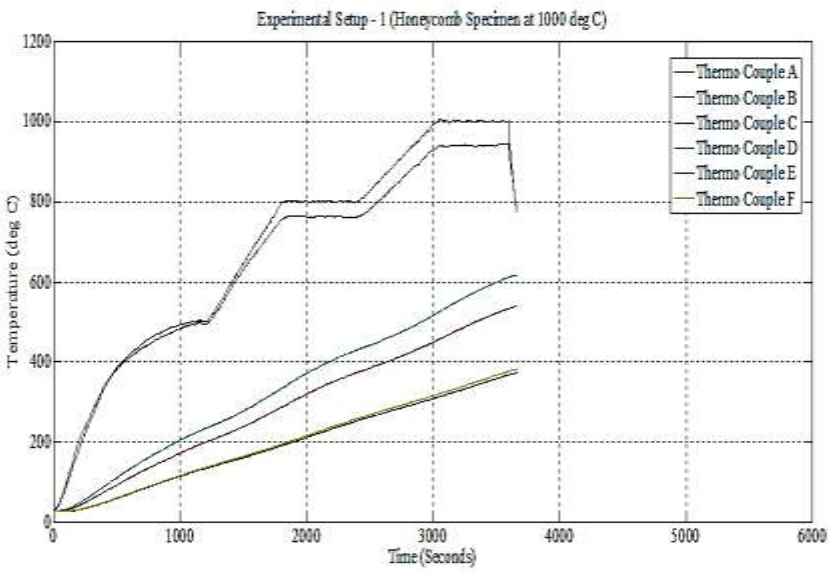

Figure A4.Experimental results 1

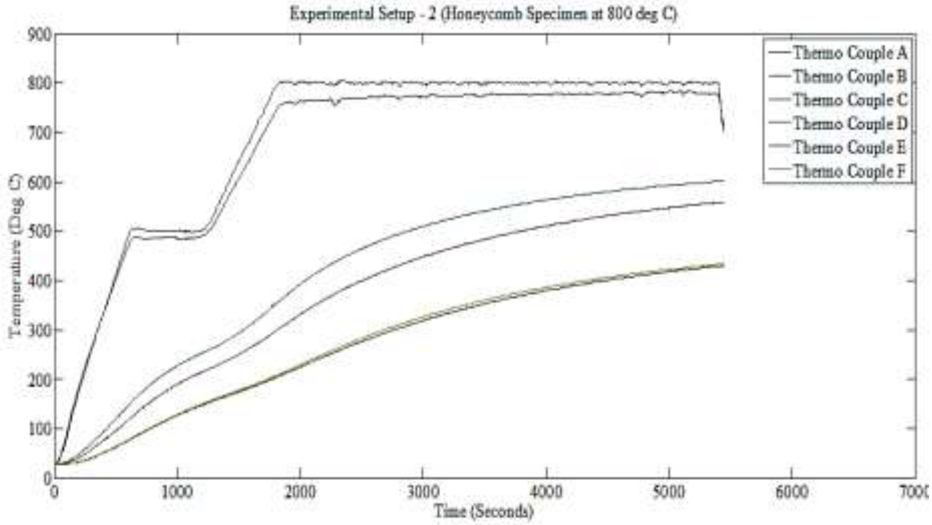

Figure A5.Experimental results 2